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RF LASER PLASMA MEASUREMENTS

W. M. Bollen

August 1984

Prepared for: Naval Research Laboratory  
4555 Overlook Avenue, S.W.  
Washington, D.C. 20375

ATTN: Dr. R. Waynant  
Code 6540

Contract No: N00014-83-C-2083

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## SECTION 1

### INTRODUCTION

#### 1.1 BACKGROUND

One of the major difficulties with excimer lasers has been the presence of impurities, introduced, for example, by the electrodes present in the D.C. discharge approach. ~~The~~ use of microwave excitation makes possible an electrodeless discharge, thereby reducing the risk of introducing impurities into the laser mix.

In this approach a tube containing the laser mix is inserted in a waveguide or microwave cavity; the microwaves then break down the laser mix to form a discharge and further interact to heat that discharge. In such microwave discharges, strong fluorescence seems limited to approximately 100 ns. In the same time frame, the fluorescence has also been observed to collapse to the wall. The wall collapse may be related to the reduced fluorescence (reduced radiating area), although "burn-up" of the lasing components seems more likely. The collapse to the wall reduces the ability to lase by decreasing the active volume. A better understanding of this effect needs to be obtained before a microwave-driven laser can be further developed.

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#### 1.2 SCOPE OF THE WORK

This research effort ~~has been~~<sup>was</sup> directed towards obtaining a fundamental understanding of the collapse of the fluorescence to the tube walls. The ultimate goal is to understand the collapse sufficiently to prevent or reduce its effects; to this end, a number of basic plasma physics experiments have been carried out. A complete understanding has not yet been reached. The results of the experiments and a statement of the present understanding of the problem are presented in the next section.

The experiments were carried out using waveguide with the tube inserted in two geometries: (1) parallel to the direction of microwave

propagation (down the waveguide), and (2) perpendicular to the direction of propagation and aligned with the electric field. Pure helium gas was used as the fill gas. Previous experiments with excimer laser mixes suggested that the collapse process was the same for pure helium as for excimer gas mixes.



## SECTION 2

### DISCUSSION OF EXPERIMENTS

#### 2.1 PERPENDICULAR TUBE ORIENTATION

In the laser experiments normally performed, the tube is parallel to the direction of microwave propagation. Our experiments were performed in this "parallel" geometry as well as in a "perpendicular" geometry, with the tube placed along the direction of the electric field for the  $TE_{01}$  rectangular waveguide mode.

One possible explanation for the collapse could be that the plasma density reaches sufficient levels for the microwave skin depth in the discharge to become less than the diameter of the tube. We would then expect the rear of the discharge to be shadowed by the front, if this were the case. However, when the experiment was performed, no shadowing was observed (for either a 1 mm or a 5 mm tube). The fluorescence appeared to start uniformly and to collapse quickly to the wall (see Figure 2.1). The final thickness of the collapsed annulus discharge was 0.3 mm. By varying the pressure, diffusion was observed to play a small role. For low pressures ( $\sim 200$  Torr), diffusion was largest (mean free path longest), and the light emission ended faster after turn-off of the microwaves than for the high pressure case ( $\sim 760$  Torr). Also, diffuse discharges (based on light emitted) lasted longer earlier in time for low pressures than for high pressures (i.e. collapse to the wall occurred faster for high pressures). This is reasonable if the process is related to peak plasma density. Since the losses to the wall are higher at low pressure due to the longer mean free path, the time to reach the critical plasma density is longer.

Although the photography suggests uniform collapse, the large reflected microwave signal implies the plasma is becoming reflective and the microwaves are not penetrating (see Figure 2.2). The uniform collapse suggests that a plasma instability must be coupling energy to the plasma at the tube walls, possibly due to excitation of surface waves.

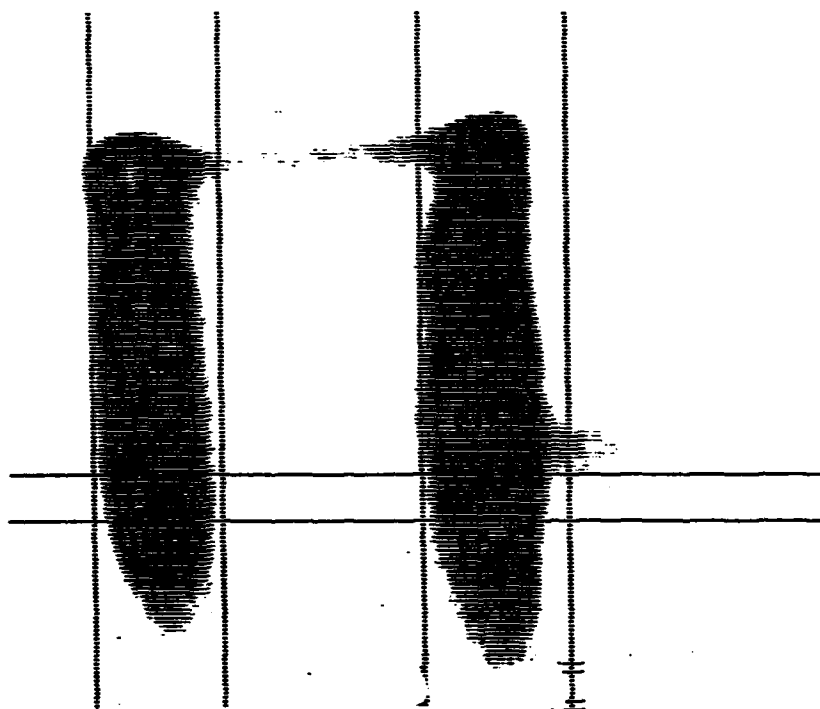
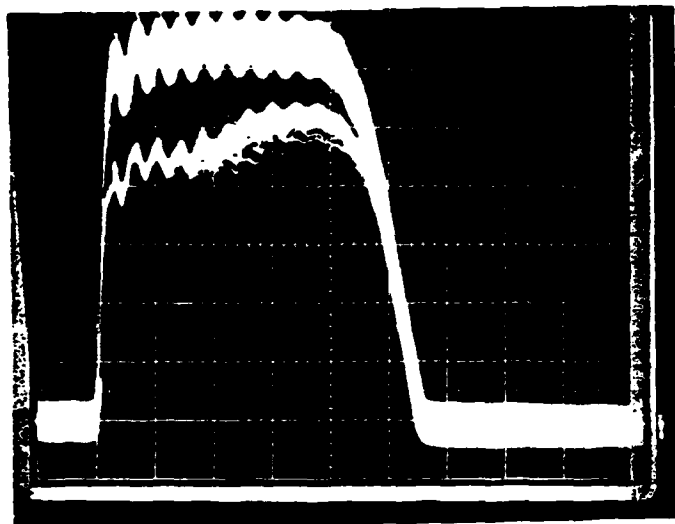


Figure 2.1 Streak photograph showing the rapid collapse of the fluorescence to the tube walls. The time duration is approximately marked for reference. The outer edges of the light correspond closely to the inner diameter of the 5 mm tube. The microwave pulse is 5  $\mu$ s long.

a)



b)

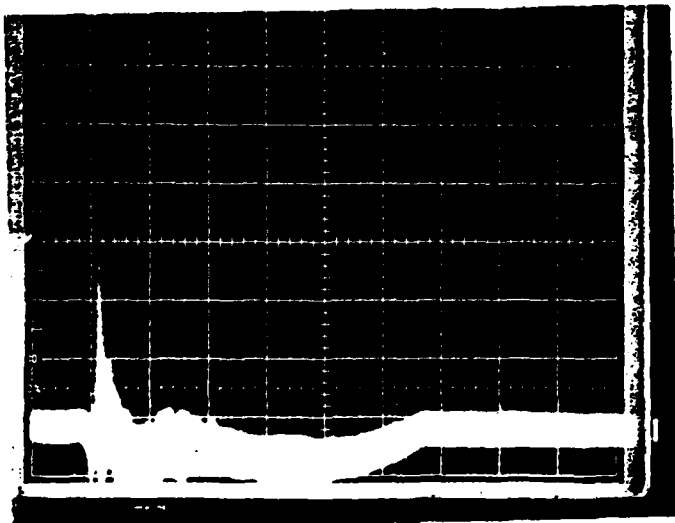


Figure 2.2 Microwave power for perpendicular geometry (horizontal scale, 1  $\mu$ s/div; vertical scale, same relative units for a) and b)). (a) Upper trace input power, lower trace reflected power, (b) transmitted power.

We conclude that the plasma density,  $n_e$ , is greater than the critical density,

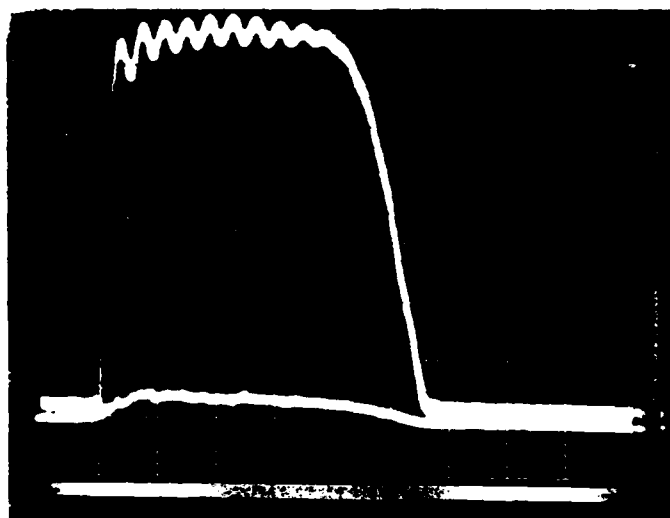
$$n_c = \frac{4\pi n_e^2}{m_e},$$

but do not as yet entirely understand the uniform collapse of the fluorescence to the walls. We do know, however, that surfaces interior to the collapse (e.g., coaxial) do not support fluorescence. It is, therefore, more than just an effect due to the surface material.

## 2.2 PARALLEL TUBE ORIENTATION

Unlike the perpendicular case, low microwave reflection has always been observed in previous parallel experiments. To confirm that the microwave reflection for the perpendicular orientation was not a result of a difference in previous experiments and is related only to tube orientation, a simple parallel experiment was performed. All other conditions were identical to the perpendicular experiments. The reflected signal was extremely low ( $\approx 5\%$ ), and about 40% of the microwave power was transmitted (see Figure 2.3). Again, the fluorescence uniformly collapsed to the walls, as shown in Figure 2.4. A possible explanation for the fluorescence collapse in this configuration (parallel) is given in the next Section. Thus, the large microwave reflection for the perpendicular direction is related only to orientation.

a)



b)

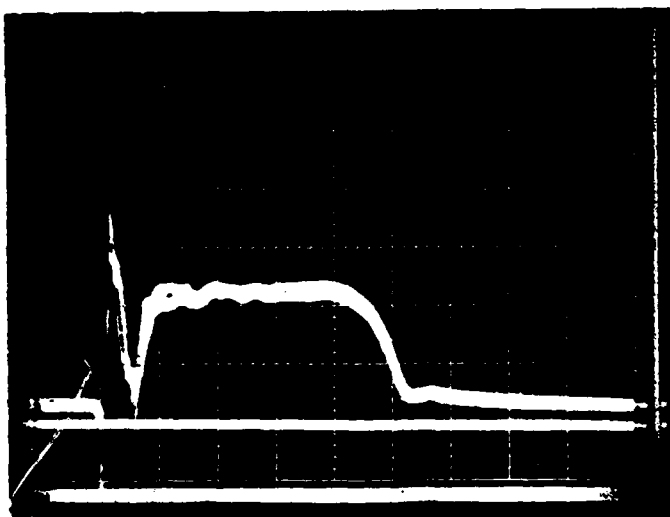


Figure 2.3 Microwave power for parallel geometry (horizontal scale, 1  $\mu$ s/div; vertical scale, same relative units for a) and b)). (a) Upper trace input power, lower trace reflected power, (b) transmitted power.

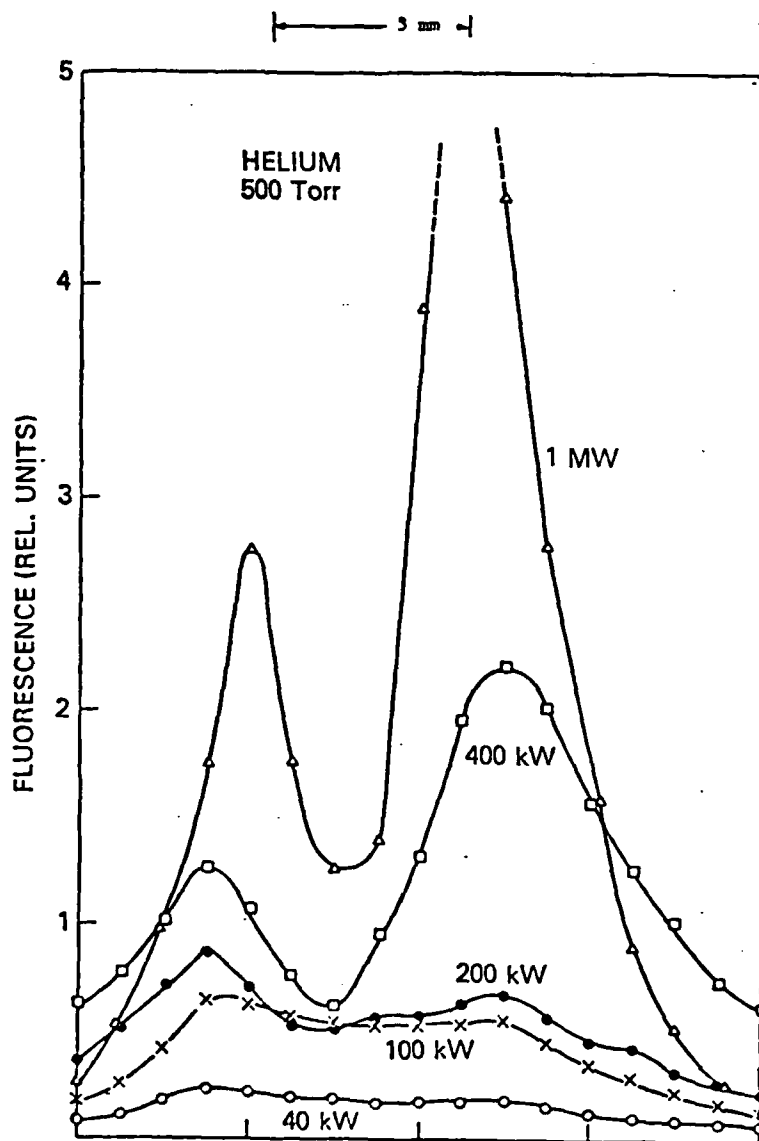


Figure 2.4 Detailed examination of penetration effect versus microwave pump power for earlier parallel geometries. Higher powers imply larger discharge density and, therefore, a larger effect.

### SECTION 3

#### EXPLANATION OF COLLAPSE

Allis and Brown (Reference 1) have a simple theory to explain the collapse of fluorescence to the walls for our parallel geometry. Their basic argument is based on the fact that the light emission is proportional to the collision frequency, which is proportional to the electric field to some power greater than one. Thus, maximum light (fluorescence) occurs for maximum field. Maximum field is determined by examining the dielectric constant:

$$\frac{1}{|\epsilon|} = \frac{(1 + \beta^2)^{1/2}}{[(r-1)^2 + \beta^2]^{1/2}} \quad (1)$$

(where  $\beta = v/\omega$  and  $r = \omega_p^2/\omega^2$ ). Realizing that  $D = \epsilon E$  is conserved, we obtain

$$\frac{E}{D} = \frac{E_f}{|\epsilon|}, \quad (2)$$

where  $E_p$  is the electric field inside the plasma, and  $E_f$  is the free space value of  $E$  ( $\epsilon=1$ ). In addition assuming that the electron density goes to zero at the walls and is greater than  $n_c$ , the critical collisionless density, inside the discharge, it can then be shown that  $E$  is maximum near the walls and, therefore, so is the fluorescence (see Figure 3.1). Unfortunately, the continuous  $D$  argument does not hold for the perpendicular geometry, and the same type of collapse is observed for this geometry, suggesting that the effect has a different cause.

The basic idea of Allis and Brown, that the maximum in light corresponds to a maximum in field, suggests that the collapse must be due to some process concentrating the field at the wall surface. Surface wave instabilities seem likely. It is well known (References 2 and 3) that

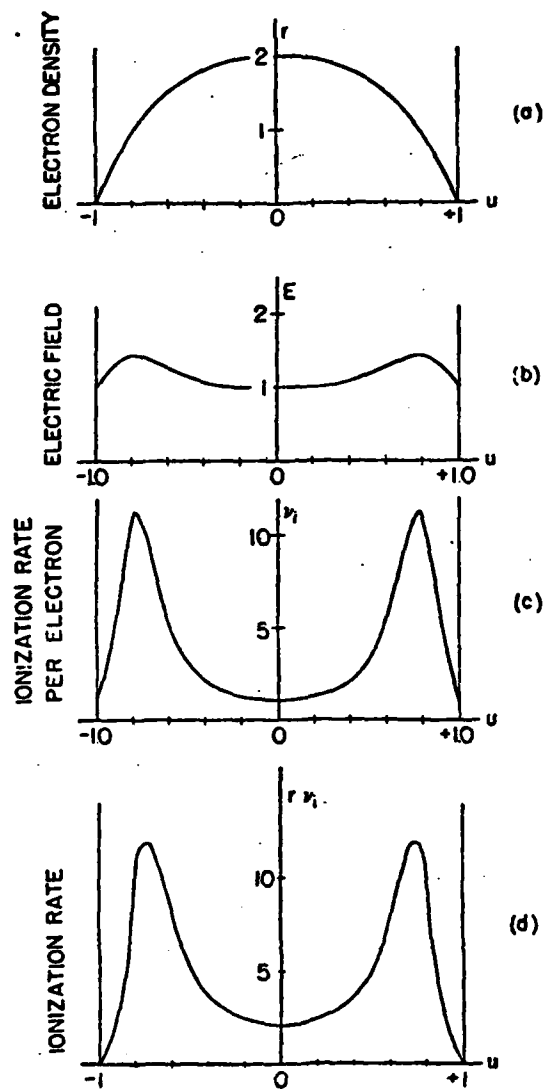


Figure 3.1 Variation of the electron density, electric field, and ionization rate across the discharge (from Reference 1). Note that the fluorescence will correspond to (d), the ionization rate.



surface waves are excited in discharge tubes inside waveguides. The basic equations are derived in Reference 2. Two types of modes exist:

1) B modes ( $H_z$ ,  $E_r$ ,  $E_\theta$ )

$$H_z \propto I_0(\tau_r) \\ (E_r \propto I_1(\tau_r))$$

and

2) E modes ( $E_z$ ,  $B_r$ ,  $B_\theta$ )

$$E_z \propto I_0(\tau_r),$$

where we have assumed azimuthal symmetry. These waves are clearly concentrated near the wall. For our parallel case, B modes can be excited, and for the perpendicular case, E modes can be excited.

The energy propagation is along the column for surface waves and can occur even where  $n > n_c$  (Reference 3). To confirm that we do, indeed, have surface waves, we examined the propagation of energy along the column. For the perpendicular case, few (almost no) microwaves should exist outside the waveguide. For no discharge in the tube using a microwave horn and with a crystal force detector, no microwaves were observed (Figure 3.2a). However, with a discharge present, microwaves were observed (Figure 3.2b).

We conclude that microwaves are coupling to surface waves, which then propagate along the discharge, which extends outside the waveguide and radiates as electromagnetic waves outside the waveguide at the end of the discharge.

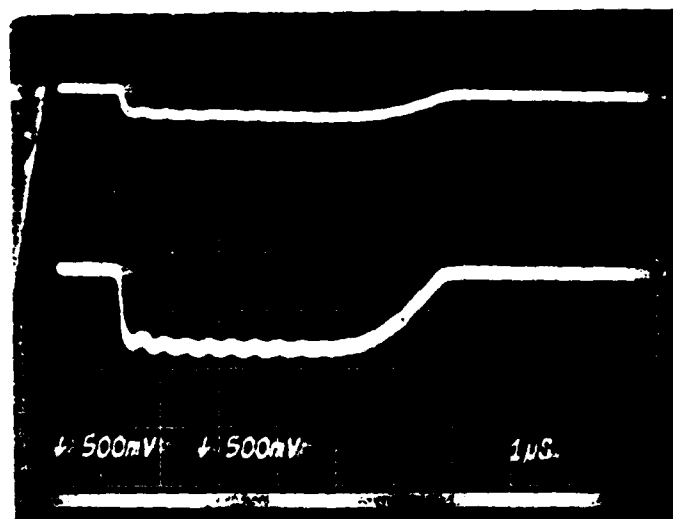
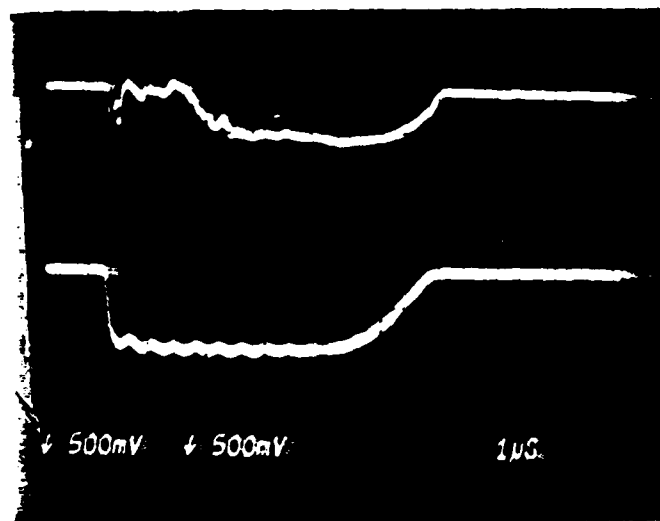


Figure 3.2 Surface wave propagation of microwave energy.

- a) No discharge in tube (upper trace horn, lower trace input power).
- b) Discharge present in tube (upper trace horn, lower trace input power).  
Note the increase in power out the tube with discharge present after some delay (growth propagation time for the surface wave).

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